METHOD FOR GENERATION OF AN ENVELOPE

[0001] The invention relates to a method for automatic generation of an envelope for a design model, available on computer, that is decomposed into finite elements by means of a prescribed meshing.

[0002] An envelope is understood as an approximate description, available on computer, of the surface of the prescribed design model by means of a set of surface elements. The envelope approximates the surface with a prescribed maximum deviation, and neglects holes, cutouts, bores, pockets, grooves and other irregularities when the dimensions thereof are smaller than the prescribed maximum deviation.

[0003] Such an envelope is required in order to simulate physical processes at the surface of a technical system by means of a finite element simulation. The technical system is simulated for this purpose by a design model that is available on computer. For example, the modeled system is an engine or a body of a motor vehicle, and the noise emission from the surface of the engine or of the body is predicted by means of an acoustic simulation. The acoustic simulation takes into consideration only processes on the surface and the adjoining surroundings, but not processes in the interior of the engine or of the body. The envelope approximates the surface only as accurately as required for the simulation so that the computing time of the acoustic simulation is as short as possible.

[0004] A software tool for acoustic and other simulations going by the name of "Virtual.Lab" is described at http://www.lmsintl.com, accessed on 10/24/2003. Mention is made of the generation of an envelope, which is called "acoustic surface meshing process" there, from a prescribed meshing. An envelope with 5000 surface elements is generated from a meshing of an exemplary drive train with 150,000 finite elements. It is not disclosed how the envelope is generated.

[0005] DE 10023377 C2 describes a method for finite element simulation. A prescribed two- or three-dimensional simulation area is covered with square surface elements or cubic volume elements. It is determined which of the grid cells lie entirely, partially or not at all in the

simulation area. How this happens is not disclosed. Subsequently, approximating functions are defined in the simulation area with the aid of B-splines over the grid points, and the simulation is carried out with the aid of these functions.

[0006] DE 10056107 A1 discloses a method for determining rattling noises in the case of motor vehicles. A design model of a vehicle is subdivided into elements and grids. Furthermore, the definition area of the model is subdivided into subdefinition areas, and the elements and grids of a subdefinition area are examined separately in each case.

[0007] The generation of a virtual wind tunnel, for example for a motor vehicle, is described in DE 19919891 A1. A prescribed design model is meshed (a "mesh" is generated), for example a surface model with 60, 000 triangular surface elements. Commercial tools are preferably used for this meshing. The design model is refined if required, for example in areas of turbulence.

[0008] The invention is based on the object of providing a method, which can be carried out with a short computing time, for automatic generation of an envelope that approximates the surface of a design model with a prescribed maximum deviation.

[0009] The object is achieved by means of the method as claimed in claim 1. Advantageous refinements are specified in the subclaims.

[0010] A meshing of the design model is prescribed. The meshing consists of finite elements with nodes. The method comprises the following steps:

- A cuboid in which the mesh of the design model is fully contained is determined.
- This cuboid is decomposed into volume elements. The decomposition is a complete one such that each point of the cuboid, and thus each point of the design model, falls into a volume element. The cuboid is decomposed such that each edge of each of these volume elements is shorter than or exactly as long as a prescribed bound. This bound is smaller than or equal to the maximum deviation to be met, and smaller than or equal to the fineness of the envelope required for the subsequent simulation.

- A check is made for each volume element of this cuboid as to whether the volume element overlaps with at least one determined finite element. An overlap is already present when the finite element and the volume element have a single point in common.
- The set of the overlapping volume elements forms a geometric body. This body is determined.
- The body is bounded from the outside by the outer bounding surfaces of the outlying volume elements. These bounding surfaces are determined.
- The envelope being sought is assembled from the set of the bounding surfaces determined in such a way.

[0011] The envelope generated according to the invention deviates from the surface to be approximated at most by a prescribed maximum deviation. The decomposition of the cuboid that completely contains the design model is carried out with a prescribed accuracy. The decomposition is carried out such that the greatest edge length of the volume elements is smaller than or equal to the maximum deviation. This greatest edge length is an upper bound for the deviation between the envelope, which is assembled from the outlying bounding surfaces of the overlapping volume elements, and the actual surface of the design model, which is approximated by the mesh. Because each edge is smaller than or equal to the prescribed bound, the maximum deviation is at most as great as this prescribed bound. This is so because the edges of the bounding surfaces are at most as long as the maximum edge length of the volume elements. Because overlapping volume elements, and no others, are selected, the method ensures that the spacing between the approximating mesh and the envelope is at most the maximum edge length, and therefore smaller than or equal to the prescribed maximum deviation.

[0012] The method renders it superfluous to vary the prescribed meshing of the design model. Computing steps, and therefore processing time, are thereby saved. This saving is the greater the finer the prescribed meshing by comparison with the maximum deviation. The method requires a maximum of M * N test steps given N cuboids and M finite elements.

[0013] The method according to the invention does not depend on how the design model has been meshed. In particular, the method can be applied both when the mesh of the design model

consists of surface elements, and when it consists of volume elements. The method can also be applied for any shape of surface elements. The cuboid is decomposed into volume elements in a fashion entirely independent of the meshing of the design model. As a result, the envelope is generated as is required by the following simulation. This following simulation can differ from that for which the prescribed mesh was generated. For example, the mesh was generated for simulation of the stresses occurring in the system, whereas the envelope is used for an acoustic simulation.

[0014] Only those bounding surfaces of overlapping volume elements are selected that bound the body formed by the overlapping volume elements from the outside. It is achieved as a result that the internal structure of the design model is not considered when generating the envelope. It is further achieved that the envelope generated according to the invention is therefore always closed and regular.

[0015] If the prescribed design model has holes, for example bores or pockets, whether approximations of these holes occur in the envelope, or whether the holes are not considered in the approximation depends on the dimensions of said holes. If the diameter of the hole is greater than the greatest edge length of the volume elements of the cuboid, at least one volume element of the cuboid lies entirely or partially in the hole, and bounding surfaces of this cuboid are outlying and belong to the envelope. The hole is otherwise neglected. Thus, which holes are considered and which are neglected is controlled by the freely selectable size of the volume elements of the cuboid.

[0016] The envelope generated has considerably fewer nodes than the prescribed mesh of the design model. A finite element simulation with the nodes of the envelope uses a system of equations with fewer unknowns, and therefore requires less computing time. This saving is particularly important when the simulation is carried out repeatedly, for example in order to compare various design states with one another.

[0017] The refinement according to claim 2 requires a particularly short computing time. The cuboid is decomposed such that the shortest edge of each volume element is greater than or equal

to the longest edge of each finite element of the prescribed mesh. The decomposition of the cuboid is freely selectable, and the accuracy with which the envelope is to approximate the surface of the design model is prescribed by the requirements of the simulation for which the envelope is being used. Therefore, it is mostly possible for the volume elements of the cuboid to have longer edges and the surface elements of the mesh of the design model.

[0018] Checking whether a finite element of the mesh and a volume element of the cuboid overlap or not is carried out in a particularly simple way by means of the refinement according to claim 2. A check is made as to whether at least one node of the finite element lies in the volume element. If such a node is found, the check is aborted, and it is decided that the volume element overlaps with the finite element. If no node of the finite element lies in the volume element, then neither can any other point lie in the volume element. This follows from the refinement that the edges of the volume element are longer than those of the finite element. Because no other point of the finite element lies in the volume element, there is no overlap between finite element and volume element. Because only the nodes, and no other points, are being examined, particularly little computing time is required.

[0019] An exemplary embodiment of the invention is described in more detail below. In the drawing:

[0020] figure 1 shows nodes of a prescribed irregular surface;

[0021] figure 2 shows a rectangle containing the surface;

[0022] figure 3 shows a decomposition of the rectangle into small rectangles;

[0023] figure 4 shows the rectangles of the decomposition that contain nodes;

[0024] figure 5 shows the resulting solid two-dimensional surface;

[0025] figure 6 shows the generated envelope.

[0026] The method according to the invention is firstly demonstrated in a simplified way with reference to a two-dimensional example. In this example, an envelope is to be generated for an irregular surface in the plane. This irregular surface takes the place in this illustration of the prescribed design model. The envelope to be generated is a set of connected lines in this plane. Figure 1 shows some of the nodes of those surface elements that belong to a meshing of the surface. For the sake of clarity, many nodes are not illustrated. The surface elements, formed by the nodes, of the irregular surface are likewise not illustrated.

[0027] A rectangle is determined in which the prescribed irregular surface and thus the mesh are contained. The irregular surface and the determined rectangle are shown in figure 2. This rectangle takes the place of the cuboid.

[0028] The rectangle is decomposed into rectangles of identical size and with prescribed edge lengths. Figure 3 shows these rectangles of the decomposition, which take the place of the volume elements, and the nodes of figure 1.

[0029] A check is made as to which rectangles of the decomposition respectively comprise at least one node of the irregular surface. These overlapping rectangles are illustrated by hatching in figure 4.

[0030] The rectangles illustrated by hatching in figure 4 form a two-dimensional surface. The cavities in this two-dimensional surface are filled up. This results in the solid two-dimensional surface shown in figure 5.

[0031] The bounding lines of this solid surface are thus assembled to form the envelope being sought. These bounding lines, which form a set of connected lines, are shown by solid lines in figure 6.

[0032] The exemplary embodiment now following relates to a component of a new motor vehicle as the technical system. The generated envelope is used, for example, for the purpose of

examining the sound emission by a solid body, for example an engine or a body of a motor vehicle, doing so by means of a finite element simulation. The sound emission is caused by structure-borne noise. This is produced by tensile stresses and/or shear stresses in solid bodies.

[0033] The sound emission is caused by vibrations at the surface of the engine or the body. These vibrations act on the surrounding air. The vibrations are decomposed into a component perpendicular to the surface and one parallel to the surface. Only the components of the vibrations perpendicular to the surface are taken into consideration in the acoustic simulation, but not the components parallel to the surface.

[0034] A distribution of the velocity of the vibrations results from the structural dynamics of the engine and its surface. This velocity is determined by an acoustic simulation. The velocity denotes the rate of deflection ds/dt, s(t) being the deflection of the sound wave perpendicular to the surface as a function of time t, and it holding that:

[0035] $ds/dt = -\omega * A * \sin(\omega t + kx + \phi)$.

[0036] The structural dynamics of the engine is calculated with the aid of a first finite element simulation. The calculated structural dynamics comprise the displacement, the velocity or the acceleration, for example the displacement of the surface. The sound particle velocity of the surface is calculated therefrom.

[0037] A design model that is available on computer is prescribed for a system, for example the engine, that is to be designed or examined. This design model is stored in a data memory of a data processing system, and preferably has the form of a three-dimensional CAD model. The design model is represented, for example, with the aid of points, curves, vectors, lines, contours, polygonal networks, curved surfaces and/or volume elements in the data memory. The method according to the invention is executed with the aid of this data processing system or another one, which has reading access to the data memory.

[0038] The method of finite elements is known from "Dubbel - Taschenbuch für den Maschinenbau" ["Dubbel - Engineering Manual"], 20th edition, Springer-Verlag, 2001, C 48 to C 50, from B. Klein: "FEM - Grundlagen und Anwendungen der Finite-Elemente-Methode" ["FEM - Principles and applications of the finite element method"], Vieweg-Verlag, 3rd edition, 1999, from T.R. Chandrupalta & A.D. Belegundu: "Introduction to Finite Element in Engineering", Prentice-Hall, 1991, and from DE 19927941 C1. A finite element simulation is used to examine physical processes of different types, for instance oscillation processes, for example the noise emission from the surface of an engine or a body of a motor vehicle.

[0039] In the prescribed design model, a specific set of points is defined that are called nodes. Those surface or volume elements whose corners are defined by nodes are denoted as finite elements. The nodes form a network in the design model, for which reason the process for defining nodes and generating finite elements is known as meshing, and the finite elements are known as meshing of the model. DE 10010408 A1 and DE 19933314 A1 describe methods for meshing a given design model.

[0040] It is possible to decompose the design model completely into finite elements when meshing. In this case, each point of the design model is associated with at least one finite element. However, an approximate solution often suffices for saving nodes, and thus leads to a smaller system of equations. If, for example, the body of a motor vehicle is being examined, it is mostly sufficient to mesh the sheet metal parts of the body approximately by means of surface elements. Joints between sheet metal parts, for example welded seams or adhesive seams, are meshed by means of volume elements. It is thereby possible for processes in the joints, for example displacements and transverse stresses, to be examined more accurately. In some applications, it suffices to mesh the surface of the design model, for example by means of a "triangulation" with the aid of triangular surface elements. The method according to invention can be applied without modification for each of these meshings. The method is prescribed any desired meshing of the design model.

[0041] Depending on the problem posed, the displacements of these nodes and/or rotations of the finite elements at these nodes and/or the stresses at specific points of these finite elements,

specifically at the integration points, are introduced as unknowns. Equations are set up which, for example, approximately describe displacements, rotations and/or stresses within a finite element. Further equations result from dependences between various finite elements. Overall, a frequently very extensive system of equations is set up with the node displacements, node rotations, stresses at integration points or further variables as unknowns, and solved numerically. Statements relating to the physical behavior of the system can be obtained by solving the system of equations.

[0042] The envelope can also be used for a simulation in accordance with the boundary element method. This method is described in Dubbel, loc. cit., C50 - C52. How an acoustic simulation is carried out with the aid of the finite element method or the boundary element method is described, for example, in Dubbel, loc. cit., O33 - O35.

[0043] Carrying out the method according to the invention requires merely the meshing of the design model. The method requires no further information relating to the design model, for example radii of curvature or chamfering, or the nature of the surface. The data processing carried out by the method inputs the meshing of the design model. In this case, the information relating to nodes and to the finite elements that is described below is input.

[0044] A node is characterized by a unique identifier, for example a running number, and its position. The identifier is unique in the mesh, for which reason two different nodes always have two different identifiers. The position of the node is characterized by an x-, y- and z-coordinate in a three-dimensional coordinate system. For example, in order to examine displacements and deformations under the influence of a loading case, it can be provided that two nodes of two different finite elements have the same position before deformation, and therefore the same x-, y- and z-coordinates. These two nodes are distinguished by different identifiers.

[0045] A distinction is made between two-dimensional finite elements, which are termed surface elements below, and three-dimensional finite elements, which are called volume elements below. Curved surfaces and bodies that are approximated by curved surfaces in space are often meshed by means of surface elements. The most common surface elements are triangles and quadrangles.

All corners of the surface elements are nodes. Sometimes use is made of quadrangles with six nodes. In addition to rectangular surface elements, it is also possible to provide other quadrangular surface elements. Surface elements are preferably described by an isoparametric representation that is known, for example, from T.R. Chandrupalta & A.D. Belegundu, loc. cit.

[0046] As a rule, use is made as volume elements of cubes and other cuboids, that is to say volume elements with six exclusively rectangular bounding surfaces. Such volume elements are often denoted as hexahedra. The eight corners of the cuboid are typically nodes of the volume element. Volume elements with eight to twenty nodes are used.

[0047] Each finite element is characterized by an identifier that is unique in the mesh, for example a running number, and by its nodes. The information relating to the finite element preferably comprises a listing of the identifiers of its nodes, and an identification of the type of finite element.

[0048] As a first step in carrying out the exemplary embodiment, the data processing system executing the method inputs the mesh. A cuboid is determined in which the mesh of the design model is fully contained. This cuboid is preferably positioned such that each of its bounding surfaces is perpendicular to a coordinate axis, and thus its edges are aligned in an axially parallel fashion. Each of the six bounding surfaces then lies in one of the following planes:

$$\{ (x, y, z) \mid x = x\_min \}, \{ (x, y, z) \mid x = x\_max \},$$
$$\{ (x, y, z) \mid y = y\_min \}, \{ (x, y, z) \mid y = y\_max \},$$
$$\{ (x, y, z) \mid z = z\_min \}, \{ (x, y, z) \mid z = z\_max \}.$$

[0049] The value x_min is calculated with the aid of the positions of the nodes of the input mesh, specifically as the smallest value of all the x-coordinates of the nodes. x_max is calculated correspondingly as the greatest value of all the x-coordinates of the nodes. y_min, y_max, z_min and z_max are calculated analogously. All the finite elements of the prescribed mesh lie inside this cuboid, because each corner point of a finite element is a node of the mesh, and because the calculation of x_min, ..., z_max ensures that all the nodes lie inside the cuboid.

[0050] The cuboid in which the mesh is contained is decomposed into volume elements. All the volume elements preferably have the same dimensions and the same geometric shape, and adjoin one another seamlessly. For example, the cuboid is decomposed into cubes of equal size. In the case when a harmonic oscillation process is to be examined by means of a finite element simulation on the basis of the envelope, how the cuboid is decomposed into cubes is laid down as follows: a half wave of the oscillation process is approximated in the finite element simulation by a set of connected lines with three lines of equal length, and a full wave is consequently approximated by six lines. The cuboid is therefore decomposed into cubes whose edge length is a sixth of the wavelength, that is to say of the length of the full wave. This wavelength is a function of the frequency of the oscillation process and of the medium in which the oscillation is propagating, and is therefore known.

[0051] A check is made as to whether the shortest edge length of the volume elements of the cuboid is greater than the longest edge of the mesh of the design model. If this is not the case, the meshing of the design model is refined.

[0052] The first step is preferably to determine or prescribe the edge lengths of the volume elements in the x-, y- and z-directions. Subsequently, the lengths of the three edges of the cuboid in the x-, y- and z-directions are divided by the prescribed or determined edge lengths of the volume elements. The three quotients are rounded off to the nearest natural numbers N_x, N_y and N_z. The number of the volume elements in the x-, y- and z-directions is thereby calculated. An actual edge length of a volume element can therefore deviate slightly from the prescribed one.

[0053] The volume elements into which the cuboid is decomposed are numbered through in running fashion. Consequently each of these volume elements is given a unique identifier. The identifier is preferably a triple (n_x, n_y, n_z) that specifies the relative position of the volume element in the cuboid. The volume element that contains the corner point (x_min, y_min, z_min) of the cuboid is given the identifier (1, 1, 1). The volume element that contains the corner point

(x_max, y_max, z_max) of the cuboid is given the identifier (N_x, N_y, N_z), N_x, N_y and N_z specifying the number of the volume elements in the x-, y- and z-directions, respectively.

[0054] The next step is to determine which volume elements of the cuboid overlap with finite elements of the mesh. To this end, a data structure is produced in the form of a table of three columns. Instead of a table, it is also possible to use a concatenated list as data structure, each list element enabling three entries.

[0055] The identifiers of the volume elements of the cuboid are entered in the first column of the table; a zero is entered in each row of the second column. Subsequently, a data structure in which the nodes of the mesh are stored is run through. It is determined for each node of the mesh which volume element of the cuboid this node fills. As set forth above, each node lies in the cuboid, and the cuboid is decomposed completely and without a remainder into volume elements. It is possible for a node to lie on the bounding surface of two volume elements adjoining one another. In the two-column table, the old entry in the second column is enlarged by one for the volume elements into which the node falls. At the end of the step, the table specifies for each volume element how many nodes lie in it.

[0056] The set of the overlapping volume elements is precisely the set of those volume elements that include at least one node and have a value greater than zero in the second column of the table. This set forms a three-dimensional body that lies completely in the cuboid. This body can contain cavities that are filled in the next step. A solid body results after the cavities have been filled. The third column of the table stipulates which volume elements of the cuboid belong to this solid body, and which do not. To this end, a one is entered in the third column of the table when there is a value greater than zero in the second column.

[0057] The volume elements that contain no node and therefore have a zero in the second column either belong to cavities in the body, or lie outside the body. The following procedure is adopted in order to distinguish these two cases: for each volume element VE that contains no node and for which no entry has yet been made in the third column, the six adjoining volume elements are determined, that is to say those that adjoin VE with a bounding surface. It is

determined which of these six adjoining volume elements contain at least one node, and which contain none. For the volume elements adjoining VE that contain no node, the adjoining volume elements without nodes that do not adjoin VE are determined in turn. These determinations are continued until either a coherent cavity that contains VE has been determined, or until the edge of the cuboid is reached. All the volume elements of a coherent cavity are "filled" by virtue of the fact that a one is entered in each case in the third column. If, by contrast, the edge of the cuboid is reached starting from VE, VE does not lie in the interior of the body, and a zero is entered in each case in the third column for VE and for the adjoining volume elements without nodes.

[0058] Cavities can also be filled up in another way. Firstly, a one is entered in each case in the third column for all volume elements that in each case have at least one node. Subsequently, a consecutive determination is made of all the volume elements that lie at the edge of the cuboid, that is to say that have at least one bounding surface that lies in a bounding surface of the cuboid. Those of these volume elements that contain no node of the mesh are outlying volume elements and are given a zero in the third column. Those volume elements that adjoin these volume elements at the edge and likewise contain no nodes are determined and are likewise given a zero in the third column. Adjoining volume elements without nodes are repeatedly determined until all the volume elements have been examined, and the third column is completely filled up.

[0059] After the filling-up process, a mesh of a solid three-dimensional body is present that comprises volume elements of the cuboid. Those bounding surfaces of this mesh are determined that bound this body from the outside. A surface model that is a meshing of the surface with the aid of surface elements is preferably produced to this end from the volume model that is the meshing of the solid body with the aid of volume elements. This step is carried out, for example, with the aid of a pre-processor for finite element tools. The first step is for a description of the meshing of the body which comprises volume elements to be stored in a file, for example in the "NASTRAN Bulk Data" data format. The "MEDINA" pre-processor is able to input a mesh from a file when the latter is present in a standardized data format, for example in NASTRAN Bulk Data. A description of MEDINA is available at http://www.c3pdm.com/des/products/medina/documentation/medina-DINA4_e.pdf, accessed on

11/27/2003. MEDINA has a functionality for producing a surface model from a volume model. This surface model is the envelope being sought.

[0060] The surface model is preferably smoothed ("relaxed"), stairsteps in the mesh being removed. The smoothing is also carried out, for example, with the aid of an appropriate functionality of MEDINA.

[0061] The envelope generated according to the invention can also be used for the purpose of visualizing results of the finite element simulation, for example the oscillation behavior or the propagation of sound. This visualization requires only the calculated physical variables at the surface of the system examined, but not the internal structure. A data reduction is carried out with the aid of the envelope. The results of calculation are converted to the surface elements of the envelope, for example by using interpolation to calculate the values of the variables at the corner points of these surface elements. The calculated variables are preferably visualized on a display screen of a data processing system, or on a paper printout. As a consequence of the data reduction, the visualization can be produced more quickly and can be varied, for example when a user wishes to rotate the visualization on the display screen, or to enlarge it.